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Experimental Operation and Future Design Considerations of a sCO2 Turbine Stop and Control Valve

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About the Authors

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Mark Stevens is an Institute Engineering at GTI Energy in the Research and Engineering Group providing requirements for component and system development and technical support for procurement and supplier management. He led major equipment procurement and installation activities for the DOE sponsored STEP Program. He holds a B.S. Degree in Mechanical Engineering from Purdue University and a MBA from Indiana University - Northwest.

ABSTRACT

The DOE STEP 10 MWe Pilot Scale sCO2 Power Plant located in San Antonio, Texas, is composed of several components that have been developed and proven as the first of a kind at greater than MW-scale. The facility which operated throughout 2023 and 2024 has completed commissioning and the first performance tests of the Simple Recuperated Cycle configuration. A low temperature, 550 °C rated, turbine stop and control (TSV/TCV) valve was installed during this time and several challenges were revealed and mitigated during commissioning and testing. The TSV/TCV experienced many conditions during operations including fast emergency closures, depressurized startups, hot restarts, and fluid hammer conditions. This paper will perform a retrospective analysis of the operational experience gained through the work of the STEP project and provide recommendations for future designs of turbine stop and control valves utilized in sCO2 systems.

BACKGROUND

The DOE STEP 10 MWe Pilot Scale sCO2 Power Plant located in San Antonio, Texas is the host site of what is currently the largest implementation of the sCO2 Recompression Closed Brayton Cycle (RCBC). At its peak power output, the cycle is expected to produce 10 MW of electricity with a turbine inlet temperature of 715°C and the main compressor inlet temperature of 35°C [1]. This implementation of the RCBC configuration utilizes 2 recuperators, known as the High Temperature Recuperator (HTR) and the Low Temperature Recuperator (LTR), and 2 coolers, for the main and bypass compressor inlet temperature controls, that are all Printed Circuit Heat Exchangers (PCHE). Aside from the turbomachinery, the other two new pieces of equipment that were developed as first-of-a-kind are the natural gas fired heater, and the Turbine Stop Valve (TSV) / Turbine Control Valve (TCV) built as a single valve. The overall RCBC configuration is shown in Figure 1. These 2 pieces of equipment were new not only because of the scale of the 10 MW plant, but also because of the operating condition of 715°C and 265 barg.

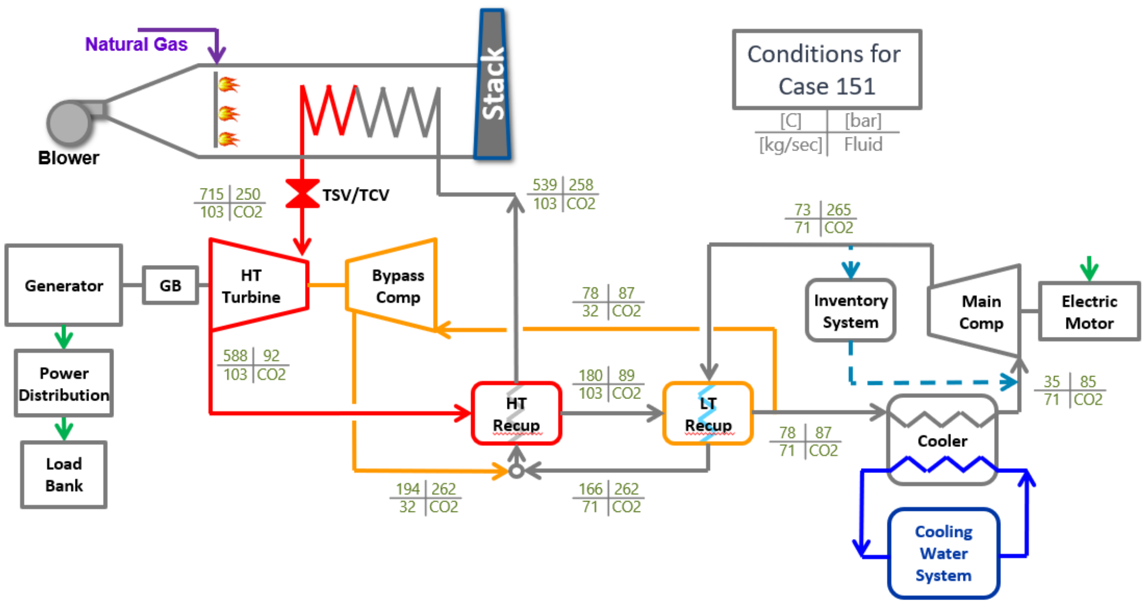

Figure 1: The RCBC configuration planned for the DOE STEP facility

While the RCBC configuration is planned for the maximum power output, a Simple Cycle (SC) configuration was also planned to aid in preliminary learning opportunities that would lower the overall risk of later operation at full RCBC temperature and pressure. Risk was additionally lowered in the SC implementation by operating at a maximum of 500°C turbine inlet temperature. The SC configuration utilizes the same physical layout as the RCBC but replaces the LTR with pipe jumpers and removes the Bypass Compressor from operations with the use of isolation valves or flange blinds. The SC configuration is shown in Figure 2. It successfully completed commissioning and operations during 2024 [2].

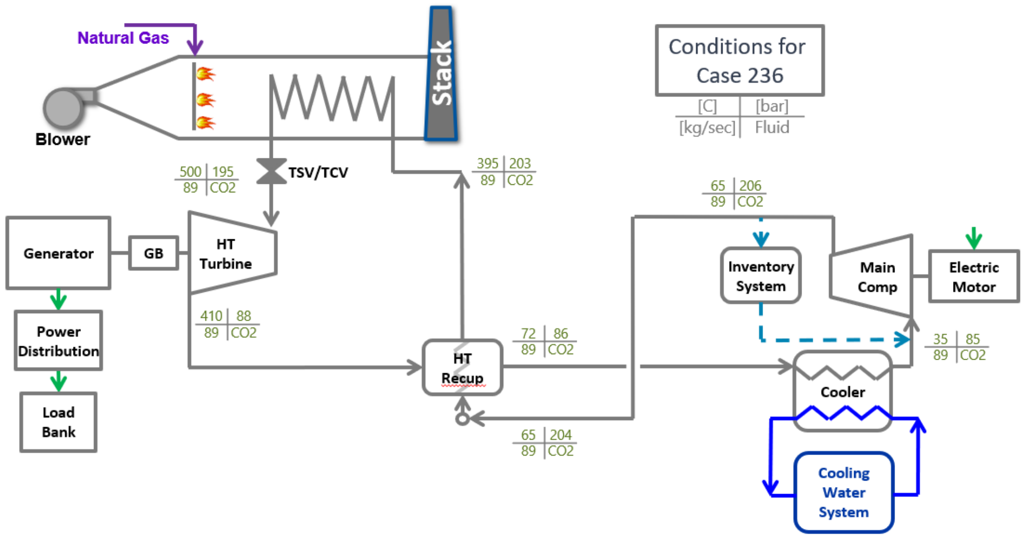

Figure 2: The SC configuration operated in the DOE STEP facility

Originally, the SC configuration was planned to operate with the same TSV/TCV as the RCBC configuration however, manufacturing challenges led to a pivot in the project plan. A lower temperature valve was procured with a more readily available valve body manufactured from stainless steel. There was minimal difference in the valve design and cost when rating for 500°C versus 550°C so the operating conditions of the low temperature TSV/TCV were selected as 550°C and 265 barg. Procurement of the low temperature TSV/TCV allowed for the SC configuration to be installed, commissioned, and tested while the manufacturing of the high temperature valve continued to work through difficulties.

The TSV and TCV were chosen to be separate valves within one valve body for several reasons. They serve different purposes from a safety perspective and perform different functions for controlling the cycle and turbine. The primary purpose of the TSV, the safety functionality of stopping the flow of CO2, helps mitigate the risk of an overspeed of the turbine rotor in the event the facility is operating near maximum power and the generator breaker opens leading to the loss of grid synchronization. The primary purpose of the TCV is to control how the cycle and turbine operate and occurs in two operating modes. During startup and shutdown, the TCV operates in speed control mode to raise, lower, or maintain the speed of the turbine train. While the turbine is at full speed and grid connected, the TCV operates in load control mode where the valve opening, and thus flow, controls the overall power output of the cycle. The TCV also operates as a safety backup for the TSV in the event of a mechanical issue with the TSV that prevents closure of the valve. While the choice to use a single body to carry both valves is not well documented, it can be understood that the single body allows for better distribution of mechanical forces and eliminates a potential leakage path at the interface between the two valves.

The focus of this paper will be the TSV/TCV combined valve, referencing the low temperature valve utilized for SC operations and the original high temperature valve for RCBC operations. This critical valve combination serves multiple safety and control purposes in addition to the harsh environment and thus requires many special design considerations. Operation of the low temperature TSV/TCV in the Simple Cycle configuration will be reviewed. The paper concludes with a focus on recommended considerations and potential future configurations of the turbine stop and control valves.

OPERATIONAL EXPERIENCE WITH THE LOW TEMPERATURE TSV/TCV

Due to various delays with the high temperature TSV/TCV, a low temperature TSV/TCV was procured for use with the simple cycle configuration of the STEP facility. Many of the requirements were duplicated from the procurement specification of the high temperature TSV with the focus being the reduction in temperature rating. The nominal design conditions for the two designs are listed in Table 1. The high temperature requirement is due to the large volume of "hot section" piping between the HTR and turbine, accounting for roughly 30% of the process volume. Due to this large volume, if the valve was placed upstream of the heater inlet, the turbine could reach an overspeed condition in the event of a trip scenario where the generator breaker opened immediately. The fast closing time requirement is partially a consequence of the specific layout of the STEP facility. The main compressor is driven by a VFD powered motor to mitigate some challenges for startup, commissioning, and trip scenarios. During simple cycle, the turbine has only the gearbox and generator which are passive inertial loads when the generator breaker is open (like in the event of a trip). Potential risk for an overspeed of the turbine could be partially mitigated by having the main compressor connected to the turbine so the compressor would act as a brake for the system when the generator breaker opens. This situation is in place for the RCBC cycle with the bypass compressor connected to the turbine, however a solution was still necessary for the simple cycle layout. However, there is a tradeoff necessary for moving the main compressor to the turbine train with multiple factors to consider. For instance the generator would need to become a motor/generator, adding complexity to the operations due to the 13 MWe size, or the facility would need to employ alternative startup methods. A custom valve was necessary so it would also meet the same flange-to-flange dimensions of the high temperature valve. One item discussed in more depth in previous papers is the need for a mechanical stop on the valve body to accommodate emergency loads during a fluid hammer event. This is discussed in more detail in [3]. Due to the high forces involved, the supplier chose to use hydraulically actuated valves.

Table 1: Nominal design conditions for two versions of the TSV/TCV

Description	High Temp		Low Temp	
	TSV	TCV	TSV	TCV
Working fluid	sCO2 (>99% pure)		sCO2 (>99% pure)	
Design Pressure	280 bara		280 bara	
Design Temperature	725 C		550 C	
Volume flow	2929 m^3/hr		2929 m^3/hr	
Nominal pipe size	8" sch 160		8" sch 160	
Minimum life	>10,000 hrs		>10,000 hrs	
Fail position/timing	closed, <200 ms	closed, <1 s	closed, <200 ms	closed, <1 s
Control accuracy	+/- 1% FS	+/- 0.2% FS	+/- 1% FS	+/- 0.2% FS

Once the valve was delivered and the piping and electrical connections were made to the valve, the commissioning process began in 2023. The TSV went through several checks and was tested to ensure the valve would close in the requested timeframe of 200 milliseconds. Based on the process volume between the TSV and turbine, and the maximum flow at full pressure and temperature, a 200 millisecond (or less) closure time would mitigate the risk of damage due to overspeed in most trip scenarios. The primary scenario that might cause damage even with the fast closure time is the failure of the coupling between the turbine and the gearbox. The TCV was tested as well to ensure tight control of valve position was achieved during operation. Initially there were concerns about valve position control because it would only follow demand within 1.5% of requested position and it displayed oscillating behavior. This is shown in Figure 3.

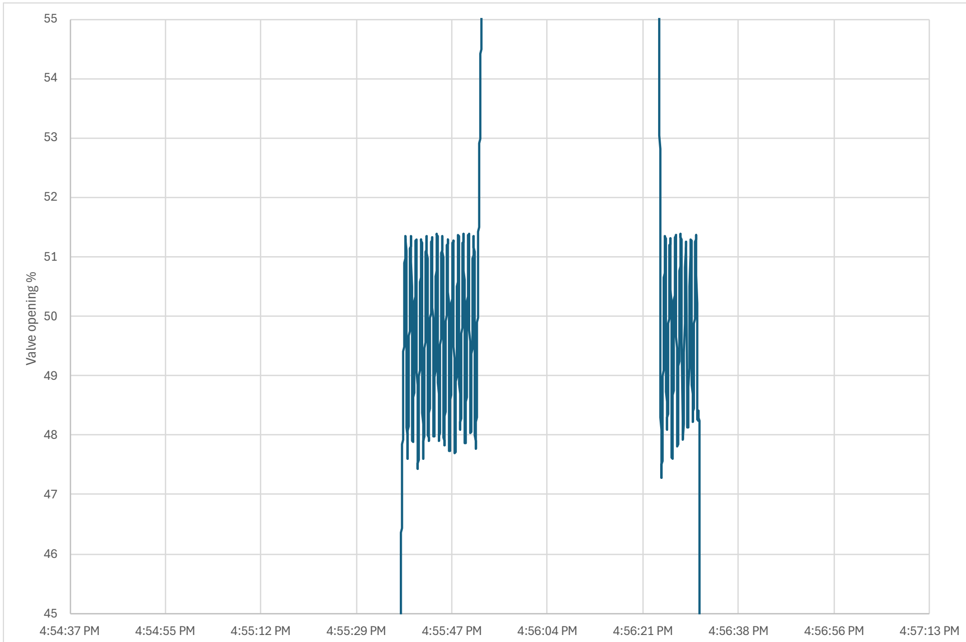

Figure 3: The original oscillating behavior of the TCV

After some initial tuning in the commissioning process the control window came down to ~0.25% of requested position and the oscillating behavior was eliminated. With large step changes in demand, some overshoot and undershoot was experienced. The maximum overshoot shown in Figure 4 was 2.7% and the undershoot was even less. AO_020 is the demand sent from the facility Distributed Control System (DCS) to the valve controller. AI_019 is the feedback of the valve position from the controller. The TSV is always fully open or closed so no tuning was performed for that valve.

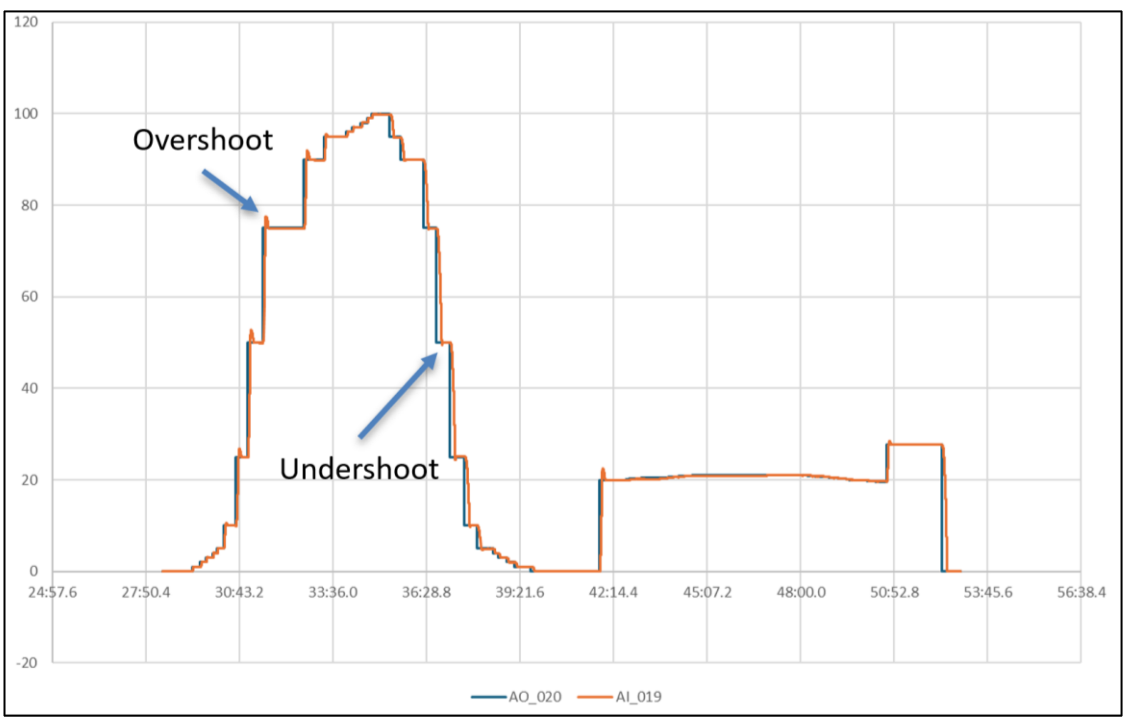

Figure 4: Test stroke data for TCV after tuning during commissioning

Both the TSV and TCV operated well throughout the commissioning process of the plant however, the TCV controller began to indicate a fault as the team approached the final commissioning tests of the plant. The fault had occurred several times over the course of a week but had automatically cleared itself with no recognizable effects on the process. While operating the plant with the turbine at full speed but not connected to the grid (the TCV was in speed control mode), the team detected a fault indication from the TCV controller. The team paused to monitor the fault and were holding the operations steady when the fault cleared. Immediately after the fault cleared, the valve position jumped 3.5% and subsequently created a turbine overspeed event. As shown in Figure 5, the valve position had already peaked and was beginning to close when the overspeed was detected and the TSV and TCV tripped closed.

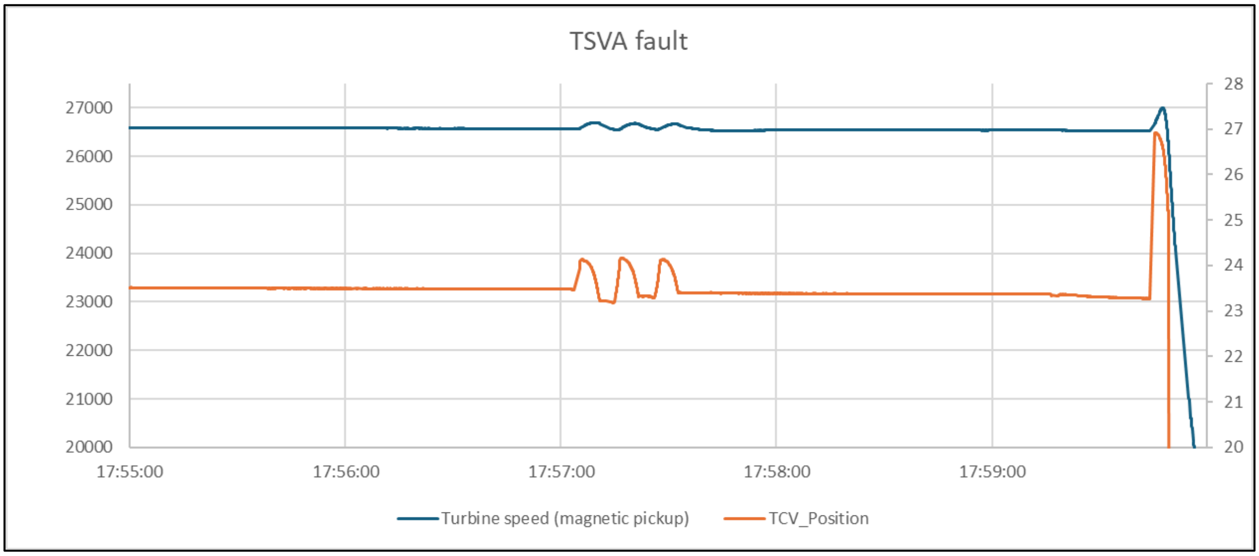

Figure 5: Minor oscillations during turbine speed control followed by TCV fault occurrence

An investigation was performed to determine the cause of the faults that had occurred. The STEP team worked with the valve supplier to gain access to the software logic in the valve controller to aid in this diagnosis. The first determination made was the valve position jumped due to integral windup during the fault time. When a fault condition exists, the hydraulic pump is not allowed to run however, the valve controller still recognized a position error that needed to be corrected. This allowed the valve to continue opening the internal hydraulic valves. When the fault automatically reset, the internal hydraulic valves were almost fully open when the pump turned on allowing a significant jump in TCV position. This was corrected by forcing the internal hydraulic valves closed and not allowing modulation in the event of a fault. The second determination was that the most likely cause of the fault was signal noise coupled with the tight deadband. As the valve slowly drifted closed due to small internal hydraulic leakage, the signal noise on the valve position feedback dropped below the position deadband and started the pump. Due to the controller PID settings, the small position error did not open the hydraulic valves enough to allow a position change before signal noise re-entered the deadband allowing the pump to stop. Due to a minimum pump runtime setting, the pump did not shut off before the signal noise exited the deadband and restarted the minimum pump run time. This allowed the pump to run continuously for 60 seconds at which time the controlled entered a fault state because the valve had not reached its desired position. This scenario was recreated while the plant was not operating and is shown in Figure 6. DI_120 is the fault indicator from the TCV controller to the DCS.

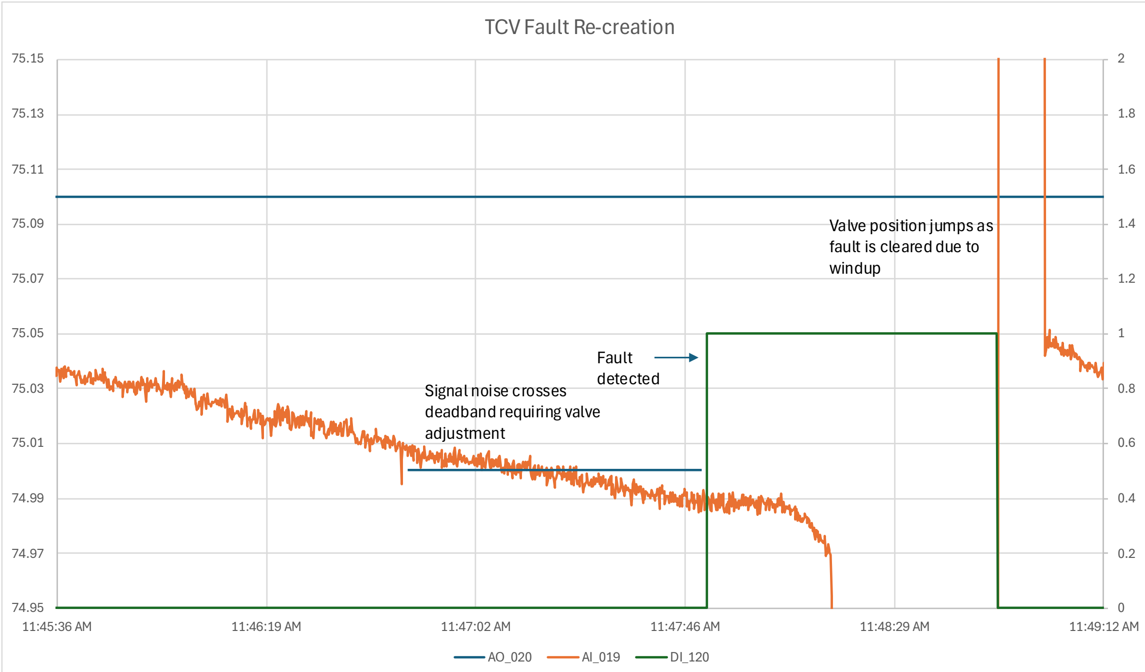

Figure 6: TCV fault re-creation data

The valve controller software was modified in collaboration with the supplier to eliminate the scenario that allowed the fault to occur. After the software modification and some retuning of parameters, the TCV was recommissioned similar to as shown in Figure 4. The maximum overshoot after this was 1.4%, which is approximately half of the original commissioning value. After these modifications were made, the valve operated throughout the simple cycle plant operations with no additional faults detected.

After simple cycle operations were complete, many inspections took place across the plant. While inspecting the TSV/TCV, some cracks on the valve seats were identified and can be seen in Figure 7. The valve was removed from service and sent to the manufacturer for repair. A simplified cross-section of the combined TSV/TCV is shown in Figure 8.

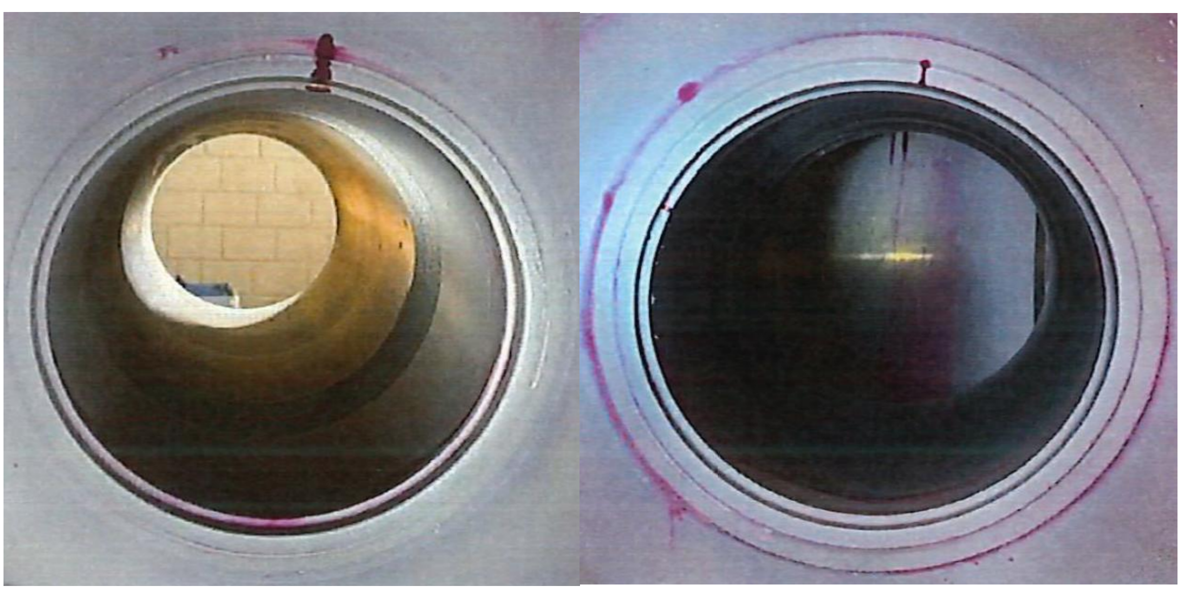

Figure 7: Cracks in valve seat of TCV (left) and TSV (right) taken after disassembly

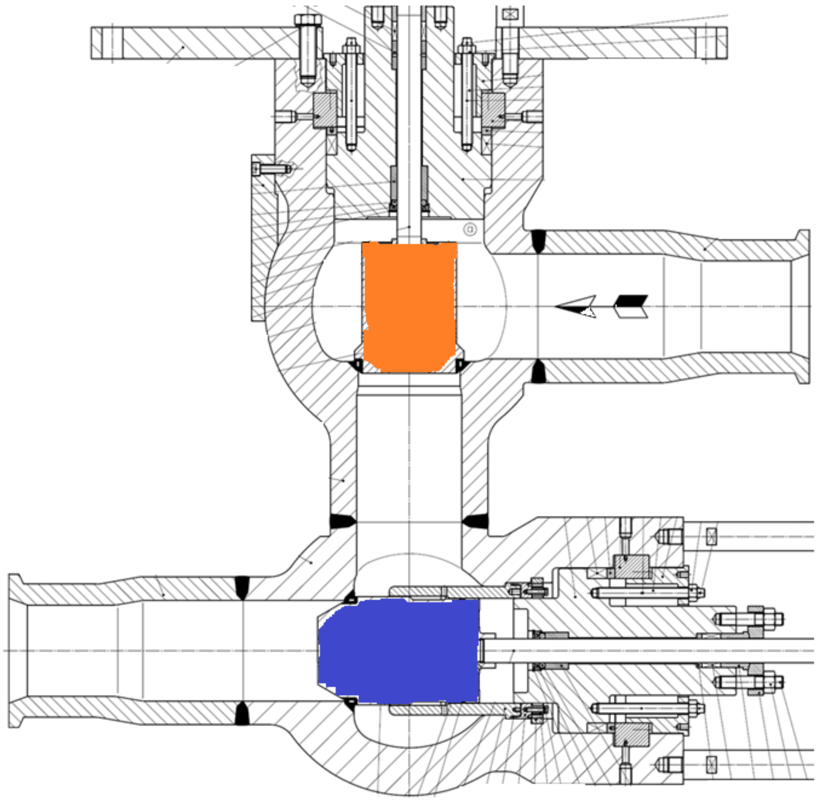

Figure 8: Cross-section of TSV (in orange) and TCV (in blue)

In both cases, the cracks occurred at the inner bore of the seat on the valve body where it mates with the plug. The plug is the blue and orange colored sections of Figure 8. Operational data and procedures were reviewed to attempt to identify the cause of the cracking. The operational data revealed that fast temperature transients were occurring during startup and shutdown of the STEP plant. Figure 9 displays one startup scenario where the plant had operated the previous day and the temperature was ~150°C prior to initiating flow through the TCV. Once flow was initiated, the temperature dropped at a rate of 40°C per minute for a short period. This is believed to be a primary factor in the creation of the cracks in the valve seat because this situation creates high thermal stresses that couple with the stresses due to pressure containment that may exceed the critical stress of the material.

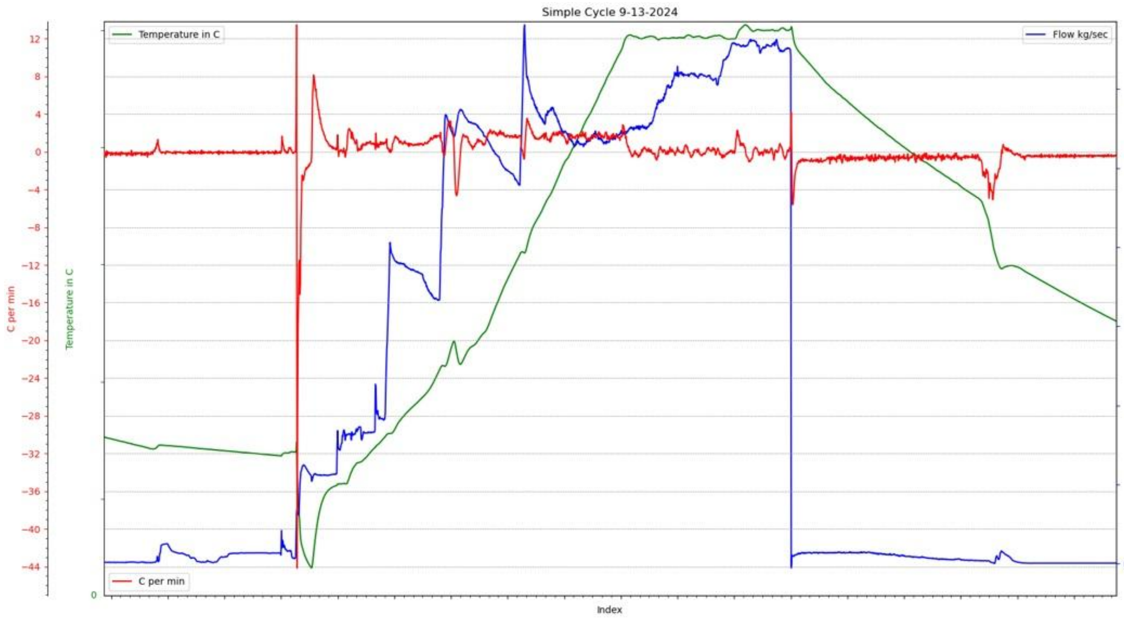

Figure 9: Operational data for the TCV outlet temperature(green) with the rate of change in temperature (red) and flow through the valve (blue) [4]

The low temperature valve was originally delivered with a welded, Stellite 6 seat material. After discussing the findings, the decision was made to modify to a clamped seat made with Inconel 718. A clamped seat style helps separate the thermal stress from the stresses from pressure containment. This also traded the long term durability (low wear) of Stellite 6 for the more ductile Inconel 718. The increased wear rate, and shorter life, of Inconel 718 was still considered acceptable for the expected life of the valve with low temperature operations of the STEP facility. The valve was modified to install the new seat designs in both the TSV and TCV and returned to the STEP facility. The valve is currently waiting to finish being reinstalled for future operations of the plant.

RECOMMENDED DESIGN CONSIDERATIONS FOR A SCO2 TSV/TCV

Based on the experience and expertise of the authors, the following list was assembled of recommended considerations when designing a sCO2 turbine stop and control valve. This list is presented in alphabetical order. Each factor must be weighed appropriately based on the intended usage and specific application. This is not an exhaustive list but is intended as a guide.

- Actuator and Valve Design
    - Accuracy of position – influences style of controls
    - Cooling requirements – dry or wet cooling
    - Duty cycle – continuous operation vs short bursts
    - Fail position
    - Flow curve (Cv/Kv)
    - Leakage class designation
    - Operating load – needs to overcome fluid forces for emergency closure
    - Precision – necessary for speed control and grid synchronization
    - Preload – related to leakage class
    - Process temperature – can lead to fire hazard in event of hydraulic leak
    - Seat type – welded, clamped, etc.
    - Stroke time – consider normal and emergency conditions
- Mechanical and Pressure Vessel Design
    - Cooling requirements (if any) – may be necessary for seal materials
    - Flaw size and location allowables

- Machinability of material
- Manufacturing method
- Operating pressure
- Operating temperature
- Pipe size and flange type
- Ramp rate (pressure) – important to prevent rapid gas decompression of seals
- Ramp rate (temperature) – important to manage thermal stress
- Sealing of valve stem
- Seat materials and finish – consider wear, thermal stresses, galling (specifically in reference to emergency closure scenario)

As indicated by the list above, there are many factors to weigh in the design and configuration decisions for a turbine stop and control valve. Some of the challenges with the high temperature valve manufacturing attempt for the STEP facility can be attributed to performing an existing process (casting) with a novel material (HA282) in a rather large body. In retrospect, it may have been more feasible to design the valve as two separate bodies with a larger mechanical interface to carry the mechanical loads experienced through various operating scenarios.

CLOSING REMARKS

In sCO2 applications, a turbine stop and control valve is a critical piece of equipment that must have robust and reliable operations. The experience gained in operating a low temperature TSV/TCV and procurement efforts for the high temperature valve by the STEP project have already helped improve the current state of the art. Not many sources are currently available to produce valves rated for greater than 700°C and greater than 250 bar. Once valves in this operating profile have proven reliability and begin to accumulate thousands of hours of operation, I expect the current system of two valves to blend into a single valve that performs all the functions of the stop and control valves.

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